Spatial Backoff in Wireless Networks

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I. Overview

Wireless channel is a shared medium and we need medium access control (MAC) protocols to regulate the channel access among multiple competing stations. Taking the set of competing stations as given, prior research on MAC protocols proposed numerous ways for each station to adjust its channel access behavior (e.g., using temporal backoff), so that transmissions from different stations may be separated in time to achieve successful transmissions. This is a temporal approach to resolve channel contention. Since the given set of competing stations may vary significantly depending on the network load, it remains a major challenge to design MAC protocols that can function efficiently under various network loads.

We propose an alternative approach for wireless networks – named "spatial backoff" – that adapts the "space" occupied by the transmissions. Wireless nodes communication over the air and there is significant interference among nodes that are spatially close to each other. On the other hand, due to radio signal attenuation, nodes that are sufficiently apart from each other are able to reuse the channel spectrum and transmit at the same time. In other words, for a node S, one can visualize the channel contention by means of contending area ω around S, where nodes located within this area compete for the channel with node S and nodes outside of this area (e.g., S1, S2, S3) may transmit concurrently with node S, as illustrated in Figure 1[1]. By spatially adjusting the contending area ω, the set of competing stations can be controlled. The goal of our project is to investigate the benefits of "spatial backoff", and devising various ways to realize it.

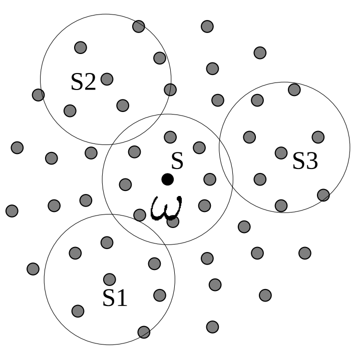

Fig. 1. Contending Area

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[1]The area is shown circular only for the sake of illustration. In general, whether a station may be allowed to transmit or not depends on the protocol design. By "transmit currently", we mean the transmissions from more than one stations overlap in time

Before making a transmission attempt, a station needs to determine whether the current channel is idle or not, what transmission power to use, and which rate to transmit at. Different choices can be made to adjust the contending area. To do so, we often need to explore the interactions between MAC and physical layers. In particular, let us consider MAC protocols based on Carrier Sense Multiple Access (CSMA). Carrier sense refers to listening to the physical medium to detect any ongoing transmissions. Only if the radio signal strength detected at a station is below a *Carrier Sense Threshold* CS_{th}, may the attempt of the station to access the channel proceed. Given a fixed transmission power used by other stations, a node will transmit more aggressively using higher carrier sense threshold values. For example, in Figure 2, station A is transmitting to B. The curve represents the signal strength versus distance for A's transmission. When station D uses carrier sense threshold CS1, D has to compete the channel access with station A. Whenever A is transmitting, D is required to defer its transmissions. On the other hand, when carrier sense threshold CS2 is used, D is allowed to transmit concurrently when A is transmitting. Therefore, a higher carrier sense threshold will lead to a smaller contending area. Similarly, given a carrier sense threshold used by other stations, a lower transmission power will lead to a smaller contending area.

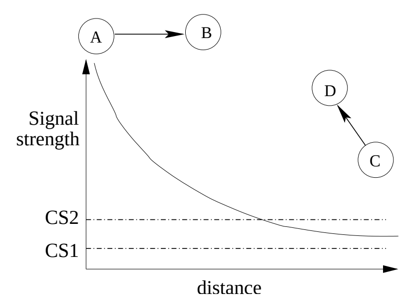

Fig. 2. Larger carrier sense threshold leads to smaller contending area

Notice that, when adjusting the contending area, the interference present in the network varies. For example, increasing the carrier-sense threshold (with a fixed transmission power) allows transmitters to be near each other and causes more interference. Typically, the quality of a communication link depends on the interference at the receiver caused by other concurrent transmissions; the higher the Signal-to-Interference-and-Noise-Ratio (SINR), the higher the rate that packets can be transmitted reliably. To account for the change of interference, the transmission rate often needs to be adjusted along with the contending area. A smaller contending area often reduces the channel contention at the cost of poorer link quality.

One possible benefit of "spatial backoff" is to improve the network aggregate throughput. From MAC protocol point of view, given a network, the aggregate throughput depends on the MAC efficiency in resolving the "local" channel contention, the number of concurrent transmissions in the network, and the transmission rate between each transmitter/receiver pair. Our study [1] shows that, when transmitter density increases, a smaller contending area is preferred to bring concurrent transmitters closer to each other. By doing this, the MAC efficiency in resolving the "local" channel contention can be improved due to the reduced number of competing stations. At the same time, spatial reuse is improved since more concurrent transmissions are allowed to proceed. Consequently, the aggregate throughput can be higher even though the transmitters may have to transmit at lower rate because of larger interference. Such a benefit of "spatial backoff" cannot be achieved by existing rate control protocols because changing transmission rate alone will not improve the spatial reuse.

II. Ongoing Research

We are investigating different approaches to implement "spatial backoff" by controlling carrier sense threshold, transmission rate or transmission power based on our prior work [1], [2]. Below, we introduce one spatial backoff algorithm, which controls the carrier sense threshold and transmission rate, assuming that the transmission power is fixed.

The goal of the spatial backoff algorithm is to find a good combination of carrier sense threshold and transmission rate so that the network aggregate throughput may approach the maximum point. Additionally, it is desirable to have a distributed algorithm so that each source station may make decisions based on its local information. To this end, we developed a model to quantify the performance at each individual station. Specifically, let $rate_i$ be the transmission rate and cs_i be the carrier sense threshold used by station i. Let p_{suc_i} denote the percentage of transmitted packets being successful for a certain measuring period, given the chosen cs_i and $rate_i$. We define a utility measure as follows,

$$U_i = rate_i * cs_i^{\frac{2}{\theta}} * p_{suc_i}, \tag{1}$$

where θ is the path loss coefficient and $cs_i^{\frac{2}{\theta}}$ is used to quantify the number of concurrent transmissions that can be possibly allowed in the network, assuming all stations use the same carrier sense threshold cs_i. The utility function defined in Equation 1 has the following desirable properties:

- By introducing p_{suc} into the utility function, we take into account the impact of MAC efficiency on aggregate throughput. If the carrier sense threshold cs_i is chosen to be too small, the local channel contention will be severe, which leads to low p_{suc_i} and bad utility measure.
- The defined utility encourages more spatial reuse. However, if cs_i is inappropriately large, the $SINR$ required by the chosen transmission rate may not be satisfied due to large interference, which leads to low p_{suc_i} and bad utility measure.
- The utility encourages to use the highest transmission rate that can be possibly supported by the $SINR$ at the receiver. However, if an inappropriately high transmission rate is chosen, its $SINR$ can no longer be satisfied. As a result, the transmission is likely to fail, leading to bad utility measure.

In essence, the utility function defined in Equation 1 measures the channel utilization per unit area. We can argue that, in dense networks, the carrier sense threshold that maximizes the above utility function approaches the point that maximizes the aggregate throughput.

Based on the utility measure, we designed a protocol for each individual station to search for the appropriate carrier sense threshold and transmission rate operating points. In Figure 3, we present ns-2 simulation results for our spatial backoff algorithm in a circular topology, in which 32 transmitters (always backlogged) are evenly distributed along a circle with a radius of 350 meters. In our simulations, the physical layer follows the specifications of IEEE 802.11a, and MAC layer follows the specifications of IEEE 802.11 DCF except that a fixed contention window size is used.

In Figure 3, horizontal axis represents the ratio between carrier sense threshold and receiving signal threshold (in dB), vertical axis represents the aggregate throughput. We first obtain the aggregate throughput for different combinations of transmission rate and carrier sense threshold. As we can see, in this example, the maximum aggregate throughput is achieved when all stations choose transmission rate as 18 Mbps and normalized carrier sense threshold as -6 dB. Our spatial backoff algorithm indeed finds the optimal point and approaches the maximum aggregate throughput, as the arrow in the figure points out.

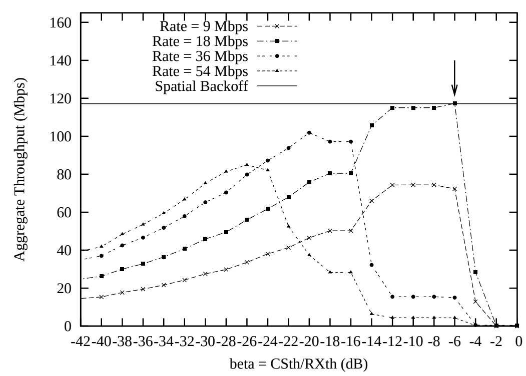

Fig. 3. Aggregate throughput for a circular topology with 32 transmitters

We have also evaluated our spatial backoff algorithm in random topologies, and the results are very encouraging.

References

[1] Xue Yang and Nitin Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *IEEE INFOCOM*, 2005.

[2] Jason Fuemmeler, Nitin Vaidya, and Venugopal V. Veeravalli, "Selecting transmit powers and carrier sense thresholds for csma protocols," Tech. Rep., University of Illinois at Urbana-Champaign, October 2004.